

DESIGN AND INITIAL OPERATION OF A SHALLOW-FOCUSING, ANNULAR, EXTRACTION APPLIED-MAGNETIC-FIELD DIODE*

J.M. Neri, F.C. Young,¹ J.R. Boller,¹ R.C. Fisher,¹ J.G. Greenly,²
D.D. Hinshelwood, T.G. Jones,⁺ B.V. Oliver,⁺ and P.F. Ottinger

Pulsed Power Physics Branch, Plasma Physics Division
Naval Research Laboratory, Washington, DC 20375 USA

¹ JAYCOR, Vienna, VA 22181 USA

² Cornell University, Ithaca, New York 14853 USA

Abstract

A 150-cm² applied-magnetic-field diode has been designed and fielded on Gamble II to produce a focused proton beam for self-pinch ion-beam-transport studies. For a beam divergence of 20 mrad, the diode should focus 200 kA of protons to < 2-cm radius at 70 cm from the anode. The diode is insulated with magnetic-fields from two coils driven by a main current of up to 50 kA and 100- μ s risetime. An opposite-polarity current pulse of 2-ms half-period, prior to the main pulse, is used to position the B-field separatrix near the anode and remove angular momentum from the extracted beam.

Introduction

The transport of intense ion beams over several meters is required for light-ion-beam inertial-confinement fusion (ICF).¹ Self-pinch transport (SPT) is an attractive scheme for this application.² For SPT, the beam is focused into a low-pressure-gas region where incomplete current neutralization provides a net current which effectively confines the ion beam within a narrow channel. With this scheme, minimal hardware is needed in the target chamber, and beam microdivergence requirements are less stringent than for some other transport schemes. STP experiments require a large proton current confined within a small radius channel. A large-area, shallow-focusing, extraction applied-magnetic-field diode (ABD) is being developed to provide proton beams for transport experiments on the Gamble II generator at NRL. Gas-interaction physics experiments and proof-of-principle SPT studies are planned.

For SPT, the net current required to confine a proton beam within a transport channel is set by the focusing geometry and the beam kinetic energy. The ion-beam microdivergence Θ_μ and the focal length F determine the focal-spot radius r_s according to: $r_s = \Theta_\mu \times F$. The radius of the transport channel r_c is $\sqrt{2}$ larger than r_s in order to match the beam envelope to the channel radius. The net current should be substantially less than the ion-beam current but sufficiently large to confine the beam. For a diode of outer radius R , the net current required to confine the beam within a channel of radius r_c scales as $I_{net} \propto (R/F)^2 V^{1/2}$, where V is the proton kinetic energy, and the ion-beam current scales as $I_{ion} \propto (R^2 V^{3/2})/d^2$, where d is the anode-cathode gap in the ion diode. The smallest diode gap, consistent with avoiding gap closure, is used to maximize the ion current and reduce the net-current to ion-current ratio.

*Work supported by DOE through Sandia National Laboratories. This work was supported in part by a grant of HPC time from the DoD HPC Center, ARL SGI Power Challenge Array.

⁺NRL/NRC Research Associate

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE JUN 1997		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Design And Initial Operation Of A Shallow-Focusing, Annular, Extraction Applied-Magnetic-Field Diode				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Pulsed Power Physics Branch, Plasma Physics Division Naval Research Laboratory, Washington, DC 20375 USA				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.					
14. ABSTRACT A 150-cm² applied-magnetic-field diode has been designed and fielded on Gamble II to produce a focused proton beam for self-pinched ion-beam-transport studies. For a beam divergence of 20 mrad, the diode should focus 200 kA of protons to < 2-cm radius at 70 cm from the anode. The diode is insulated with magnetic-fields from two coils driven by a main current of up to 50 kA and 100-ps risetime. An opposite-polarity current pulse of 2-ins half-period, prior to the main pulse, is used to position the B-field separatrix near the anode and remove angular momentum from the extracted beam.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 6	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

Diode Design

Several constraints determine the final design of the ABD, which is illustrated Fig. 1. The design and construction are based on proven diode performance at Cornell,³ Karlsruhe,⁴ and Sandia.⁵ Two magnetic-field (B-field) coils, inner and outer, are used. A diode with a large outer radius will have a larger-area anode, more ion current, and easier diagnostic access. However, the outer radius of the anode ion-source is limited to 10.5 cm in order to fit the diode within existing hardware on Gamble II. The anode inner radius is constrained to 8.0 cm due to ion-beam defocusing by the inner-coil B-field and the stress limit on this coil. The B-field coils are connected in series to an external capacitor bank, and a shunt inductor is used to adjust the ratio of the inner- and outer-coil currents and the B-field shape in the gap between the anode and the cathode tips. To match the 2- Ω Gamble II impedance to this higher impedance diode, a parallel load is used prior to the ABD, as shown in Fig. 1. The parallel load clamps the Gamble II insulator voltage and prevents insulator flashover. The ion beam is extracted through a 2- μm thick polycarbonate foil (Kimfol) into 1-Torr air where the beam is current neutralized and ballistically directed to focus. The diode design is based on generating and focusing 200 kA of 1.5-MeV protons out of a total ion current of 250 kA. For 20-mrad microdivergence, the beam is focused into a 1.4-cm-radius spot at 70 cm from the anode. To optimize the focused beam intensity, the anode ion-emitting area is offset radially (upwards in Fig. 1) from the gap between the inner and outer cathodes and a shaped, flux-excluding anode is used. A passive (wax-filled-groove) anode is used in initial experiments, but an EMFAPS system⁶ can be fielded because the interior of the anode is empty. A large focal length provides small-angle ion trajectories into a transport channel for ease of confinement. The ATHETA code⁷ is used to calculate magnetic fields and ion-beam focusing trajectories for a shaped anode. These calculations include the effects of an aspheric anode shape, the applied-B fields, and the ion-beam self-fields, as shown in Fig. 2 for a 1.5-MeV, 200-kA proton beam. No B-field penetration into the anode structure or beam microdivergence is included in these calculations. Without any B-fields, the proton beam converges, but is highly defocused. With an applied B-field, focusing occurs at 70 to 80 cm from the anode. With both applied and self fields (all fields), the beam is well focused near 70 cm. To obtain this focusing, an aspheric convex anode shape is required.

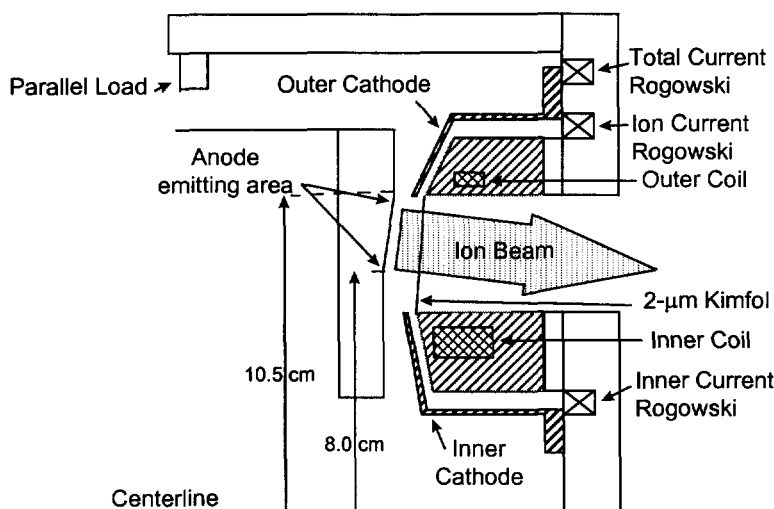


Figure 1. Schematic of the shallow-focusing extraction ABD designed for Gamble II.

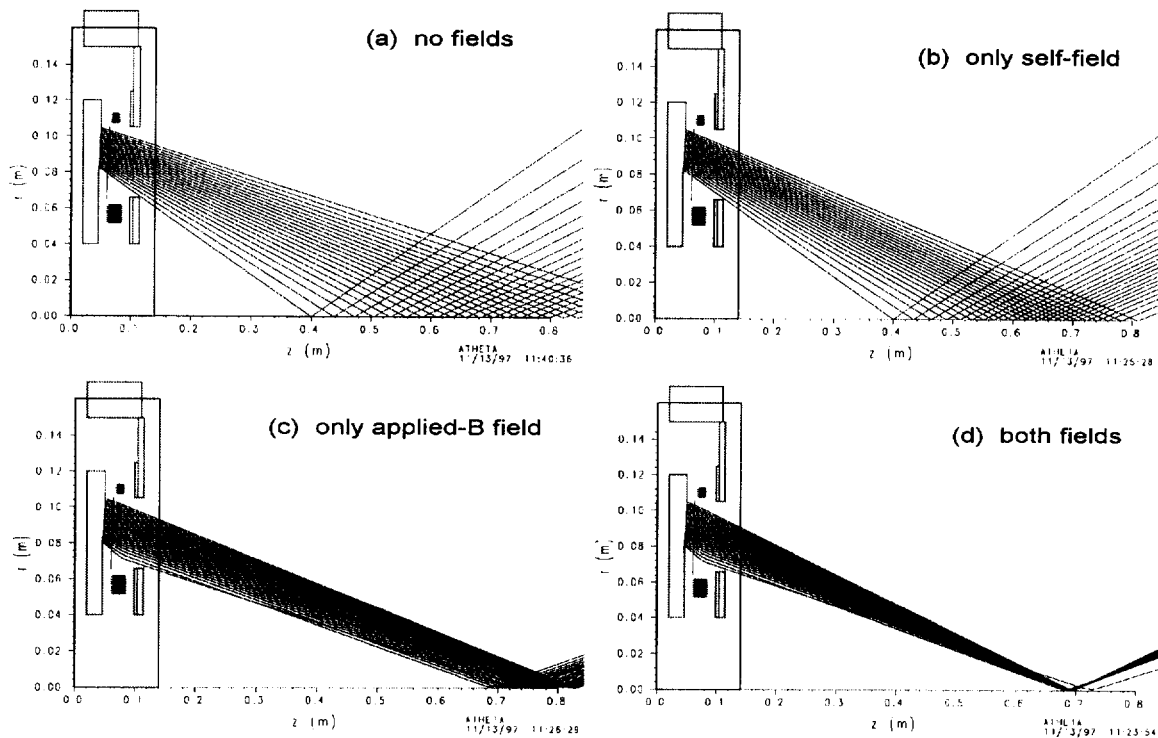


Figure 2. Calculated ion trajectories for a shaped convex anode with (a) no fields, (b) only the ion-beam self-field, (c) only the applied-B field, and (d) both fields.

Diode Operation

Initially the diode is operated with a simple wax-filled-groove anode to evaluate the coupling of the ABD to Gamble II and to adjust the anode-cathode gap and applied field to give stable impedance behavior. The peak diode voltage is limited to 1.2 MV by adjusting the Gamble II output and the parallel-load impedance. The total coil current and the shunt inductance are varied to control the applied field. The 4- Ω parallel load carries most of the current from Gamble II. ABD operation at $\approx 20 \Omega$ is shown in Fig. 3. The total current delivered to the ABD and the extracted ion current are measured with Rogowski monitors shown in Fig. 1. A peak total current of 60 kA and a peak ion current of 40 kA are obtained in these experiments. The beam focuses at 70 cm to a radius of ≈ 4 cm, as measured with witness plates and radiachromic film.⁸ The proton fraction of the beam within 4.7-cm radius at 70 cm was determined by carbon activation⁹ to be $(45 \pm 5)\%$ of the beam extracted from the diode. This fraction is consistent with other passive anode measurements.¹⁰ To reduce the size of the focal spot, angular momentum must be removed from the beam as described in the next section.

Operation with Counterpulse

The ion-beam-emitting surface must be positioned at the separatrix to prevent angular momentum from being imparted to the extracted ion beam. The B-field soaks into the aluminum anode during the 100- μ s risetime of the main-current pulse so that the separatrix is located within the anode hardware. Also, anode plasma expansion (≤ 1 mm) into the anode-cathode gap moves the ion-emitting region farther from the separatrix and adds additional angular momentum to the beam. To control the position of the separatrix, an opposite-polarity, 2-ms half-period

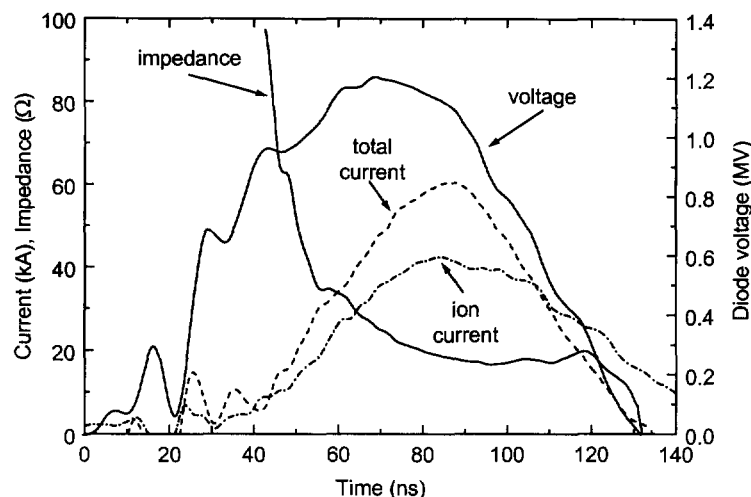


Figure 3. Measured ABD voltage, total current, impedance, and extracted ion current for a 7-mm anode-cathode gap without counterpulse.

counterpulse is applied to the coils prior to the main pulse.¹¹ Substantial inductance ($110\ \mu\text{H}$) is used in the counterpulse capacitor bank to obtain a long ring time and to isolate the two capacitor banks. The main bank is fired near zero current of the counterpulse bank, as shown in Fig. 4, and the ABD is fired at the peak of the main-bank current pulse. The effect of the counterpulse B-field on the beam focus is evaluated with ATHETA code calculations which include field penetration of the diode hardware. With all B-field components, the calculated focal radius

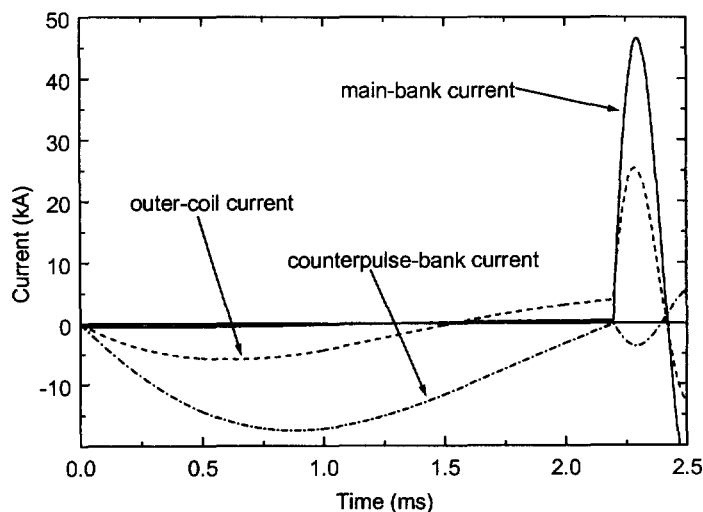


Figure 4. Currents to the B-field coils from the counterpulse bank (2-ms half period), the main bank (0.1-ms risetime) and the current shunted to the outer coil for shot 6909. The inner-coil current is the sum of both bank currents.

without beam microdivergence is much less than the 1.4-cm radius determined by the beam microdivergence.

Experimentally, a multiple-pinhole camera is used on Gamble II to determine where the ion beam is going and to demonstrate that the B-field from the counterpulse current removes angular momentum from the extracted ion beam. The beam is imaged through a two-dimensional, radial array of 1-mm diameter pinholes onto radiachromic film.⁸ Images of the anode emission, measured at 53 cm from the anode, are shown in Fig. 5 for shots without and with the counterpulse. These images are recorded at $\times 10$ demagnification so that the 21-cm diameter anode is contained within a 2.1-cm diameter image. Each annular image in Fig. 5 is recorded through a separate pinhole. The central (half-annulus) image for each shot in this figure is located on the diode axis and is less intense than the nearby off-axis images because the annular beam is still converging at 53 cm. For off-axis images, the azimuthal region of the annular ion source close to the pinhole is more intense. For shot 6873 without the counterpulse, ions from this intense azimuthal region are directed off-axis. As the counterpulse current is increased, the direction of these ions moves closer to the axis. For shot 6909, a peak counterpulse current of 18 kA (see Fig. 4) is sufficient to direct these ions toward the axis, i.e., remove angular

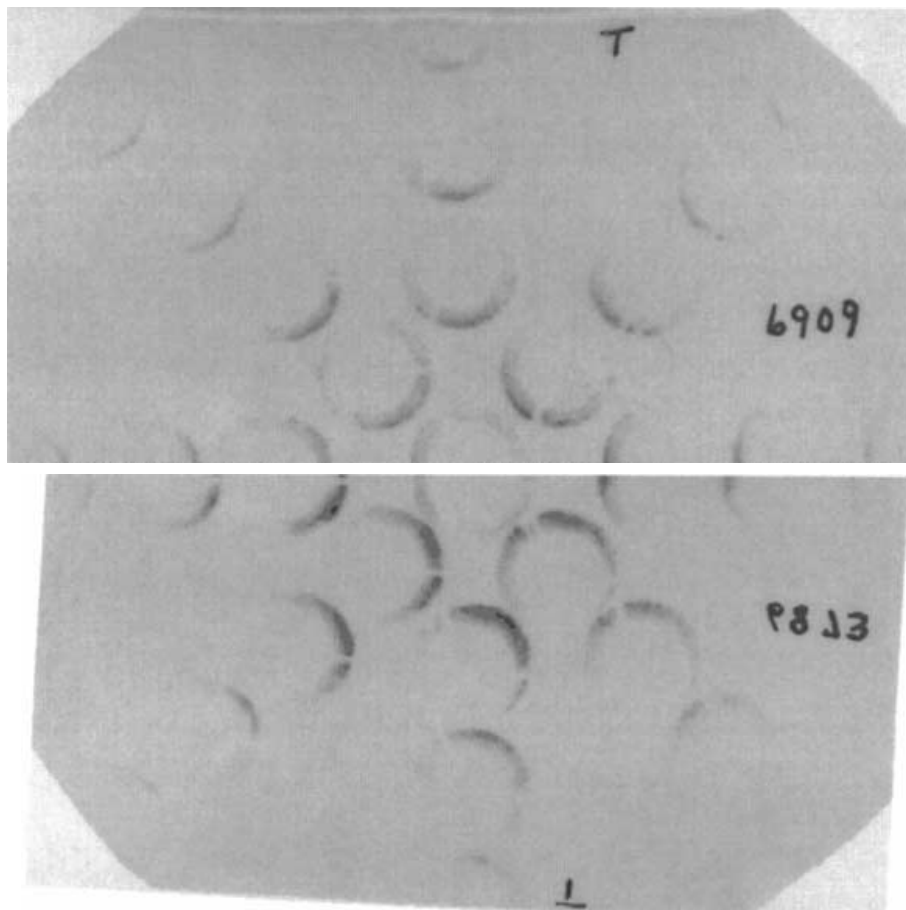


Figure 5. Radiachromic film images of ion emission from the anode for similar shots: 6873 without counterpulse (bottom) and 6909 with counterpulse (top). Pinholes on the 45° axes are spaced 2 cm apart. On 90° and 0° axes, the initial pinhole spacing is 3 cm followed by 2 cm.

momentum from the beam. Using the counterpulse to correct the ion-beam aiming to axis should reduce the focal-spot radius to 1.4 cm. For the diode B-field configurations used in these initial experiments, the field associated with the counterpulse inhibits electrons from the parallel-load region from entering the diode thereby limiting the ion-emitting area of the anode and the enhancement of ion emission so that the total beam current is only 60 kA (see Fig. 2). Adjustments to the shape of the B-field in the anode-cathode gap are expected to increase this current substantially.

Summary

An 10.5-cm outer diameter extraction applied-magnetic-field diode has been designed and fielded on the Gamble II generator to produce focused proton beams for self-pinched ion-beam-transport studies. A two-coil system with a main current pulse and a counterpulse current pulse are used to remove angular momentum from the beam. Robust B-field coils have provided up to 4.8 Tesla in the anode-cathode gap and 10.7 Tesla at the inner-coil surface without failure for more than 100 shots. An aspheric convex anode shape is required to produce a shallow-focusing beam. Initial experiments with passive anodes demonstrate stable impedance behavior at 1.2 MV and 60-kA peak total current. A 4-cm focal radius, measured without the counterpulse, should be reduced by more than a factor of two with a counterpulse to remove angular momentum and with an anode shape better tuned to the experimental operating conditions. Tuning of the B-field shape, anode-cathode gap, and B-field strength to produce more uniform and more intense ion emission over a larger anode area is continuing. Additional increase in the beam current is expected when the diode is operated at 1.5 MV. An active anode source (EMFAPS) is planned to reduce the ion turn-on time and to increase the proton fraction of the beam.

References

1. J.P. Quintenz, *et al.*, Prog. Nucl. Eng. **30**, 183 (1996); and D. Mosher, *et al.*, in Proceedings of the 8th International Conference on High Power Particle Beams, B.N. Breizman and B.A. Knyazev, Eds. (World Scientific Press, Singapore, 1991) p. 26.
2. D.R. Welch, *et al.*, Phys. Plasmas **3**, 2113 (1996).
3. J.B. Greenly, *et al.*, in Proceedings 10th International Conference on High Power Particle Beams, W. Rix and R. White, Eds., NTIS No. PB95-144317, 1995, vol. 1, p. 398.
4. H.J. Bluhm, *et al.*, Proc. of the IEEE **80**, 995 (1992).
5. M.P. Desjarlais *et al.*, in Proceedings 11th International Conference on High Power Particle Beams, K. Jungwirth and J. Ullschmied, Eds., NTIS No. PB95-144317, 1996, vol. 1, p. 101.
6. see for example H.P. Laqua, *et al.*, J. Appl. Phys. **77**, 5545 (1995), and references therein.
7. J.P. Quintenz, *et al.*, Laser and Particle Beams **12**, 283 (1994).
8. F.C. Young, J.R. Boller, and S.J. Stephanakis, in Conference Record - Abstracts, 1994 IEEE International Conference on Plasma Science, IEEE Catalog No. 94CH3465-2, p. 133.
9. F.C. Young, J. Golden, and C.A. Kapetanakis, Rev. Sci. Instrum. **48**, 432 (1977).
10. J.B. Greenly, *et al.*, in Proceedings 9th International Conference on High-Power Particle Beams, D. Mosher and G. Cooperstein, Eds., NTIS No. PB92-206168, 1992, vol. 1, p. 43; and D.J. Johnson, *et al.*, J. Appl. Phys. **50**, 4524 (1979).
11. D.J. Johnson, *et al.*, J. Appl. Phys. **58**, 12 (1985).